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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	June 1995.	Jan 95-Jan 95

4. TITLE AND SUBTITLE
A Novel mm-Wave Heterojunction JFET Technology with Suppressed Hole Injection

5. FUNDING NUMBERS

6. AUTHOR(S)
Professor Umesh K.Mishra

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Department of Electrical & Comp. Engg.,University of California, Santa Barbara, CA 93106.

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U. S. Army Research Office
P. O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

12a. DISTRIBUTION / AVAILABILITY STATEMENT
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12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

It is necessary for a good compound-semiconductor device technology to be simple and relatively transparent to the two commercially important families of materials namely GaAs and InP based. The technology should be uniform, high performance and low cost to penetrate crucial large volume markets. The lack of a large bandgap insulator(with low surface states) in III-V materials eliminates the choice of an insulator gate technology. Further, InP based Schottky-barrier gate technology is limited by the low Schottky barrier height (0.6 eV) on AlInAs and the gate recess non-uniformities. We have developed a InP based device technology which incorporates a p-n junction barrier as the gate. This results in low gate leakage and a high breakdown voltage. Most importantly, the gate to channel separation is determined solely by MBE growth which leads to a reproducible gate barrier height which translates to high threshold uniformity. The latest results include the development of p+InGaAs/AlInAs/n-InGaAs Junction Modulated HEMTs (JHEMTs) with cutoff frequencies f_τ and f_{max} of over 100 GHz and 200 GHz respectively, with an associated threshold voltage uniformity of 13.6 mV. This report describes this and the other important results obtained with the JHEMT technology.

14. SUBJECT TERMS	15. NUMBER OF PAGES	16. PRICE CODE
	13	

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std Z39-18

19951006 006

DTIC QUALITY INSPECTED 5

Novel mm-Wave Heterojunction JFET Technology With Suppressed Hole Injection

INTERIM TECHNICAL REPORT

Umesh K. Mishra

June 1995

U. S. ARMY RESEARCH OFFICE

CONTRACT No. DAAH04-93-G-0033

Department of Electrical and Computer Engineering,
University of California, Santa Barbara, CA 93106.

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A. Problem Statement

The development of a good compound-semiconductor device technology for integrated circuits would require a simple transistor technology that is relatively transparent to the two commercially important families of materials, namely GaAs and InP based. The technology should be uniform, high performance and low cost to penetrate crucial large volume markets such as signal processing and wireless communication.

The lack of a large bandgap insulator (with low interface states) in III-V materials eliminates the choice of an insulator barrier gate technology. Further, InP based Schottky-barrier gate technology is limited by the low Schottky barrier height (0.6 eV) on AlInAs, and the gate recess non-uniformities. The horizontal and vertical variations in the recess etch of the Schottky HEMT prevent high threshold uniformity, reproducible state-of-the art noise performance, and the maturation of a high yield, low cost MMIC technology.

We have developed a device technology using n-AlInAs/GaInAs on InP substrate, where the gate technology incorporates a p-n junction barrier (fig 1). The p-n junction, that exists between the p+ InGaAs surface layer and the two dimensional electron gas (2DEG) in the channel, exhibits low gate leakage and a high breakdown voltage. Most importantly, the gate to channel separation is determined solely by MBE growth which leads to a reproducible gate barrier height which translates to high threshold uniformity.

The problems of gate contact resistance and hole injection associated with the junction barrier gate technology are addressed by very high acceptor doping and the large hole barrier provided by this material system. We have succeeded in developing a high performance, uniform (threshold uniformity σV_{th} = 13.7 mV) Junction-Modulated HEMT (JHEMT) technology, with unity gain cutoff frequency f_τ of 105 GHz and unity power gain cut-off frequency (f_{max}) to 220 GHz which is the highest f_{max} reported for a junction-barrier FET (JFET).

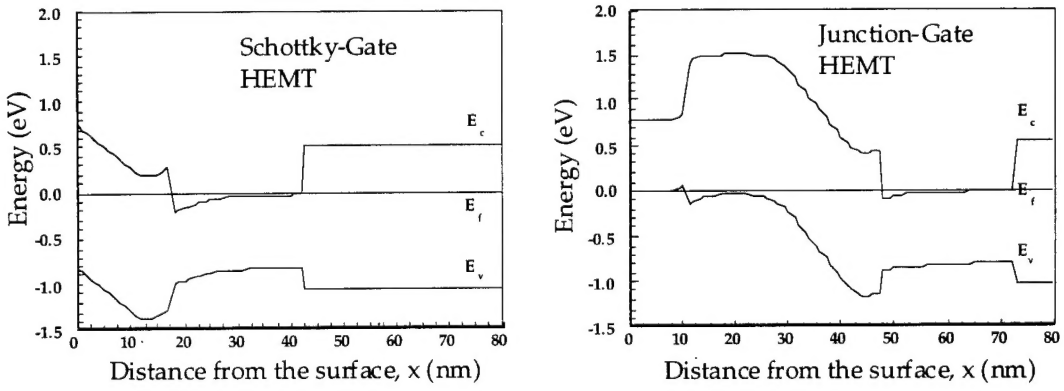


Figure 1. Comparison of band-diagrams of Schottky-Gate and Junction-Gate HEMTs.

B. Summary of results.

Results of different device structures and concepts that were investigated in order to develop the desired technology are summarized in this section.

1. Single-Doped p+AlInAs/n-AlInAs/GaInAs JHEMTs.

The device structure investigated here was the p+AlInAs/n-AlInAs/GaInAs JHEMT. The gate barrier is determined by the work function between the neutral p+ gate layer and the 2DEG, which may be as large as the energy bandgap of the chosen gate material, 1.4eV for AlInAs (for a conventional Schottky HEMT, this value is 0.6 eV). The performance of both 1μm and 0.2μm gate length p^+-AlInAs/n-AlInAs/GaInAs JHEMTs with regrown ohmic contacts is reported.

The 1 μm device is shown in fig 2. Both devices show good pinchoff characteristics, similar transconductance (220-240 mS/mm) and current density (250-300 mA/mm).

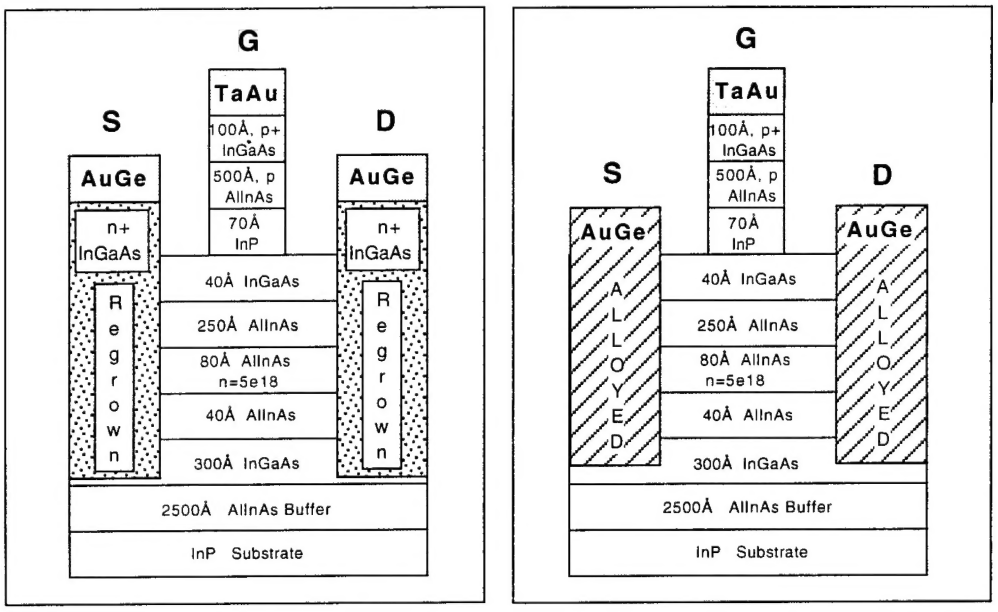


Figure 2. 1-μm gate length p+-AlInAs/n-AlInAs/GaInAs JHEMT structures fabricated. Both regrown ohmic contact (left) and alloyed ohmic contact (right) technologies were utilized.

The main point here is that uniform, non-alloyed regrown contacts contribute to higher breakdown voltages than the standard alloyed contacts. The gate-drain breakdown voltage of the regrown sample is 31 V which is 40 % higher than the 22V breakdown for the alloyed sample (fig 3).

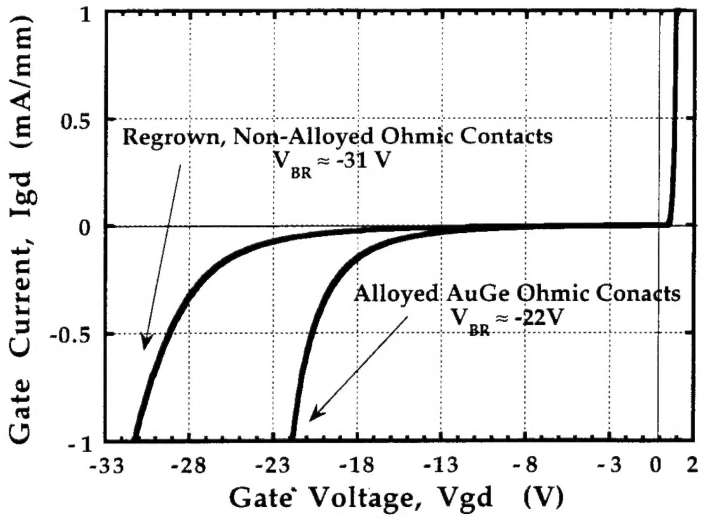
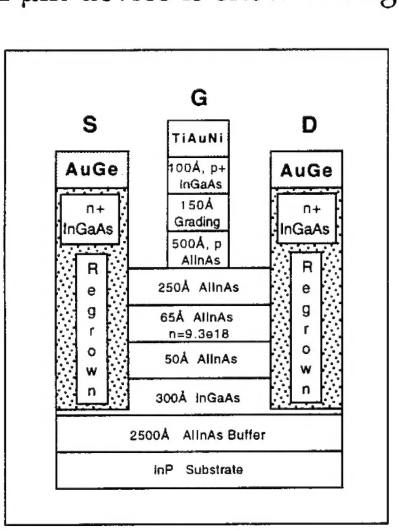


Figure 3.. Room temperature dc two-terminal gate-drain diode characteristics of the 1-μm gatelength JHEMTs with non-alloyed regrown ohmic contacts and alloyed ohmic contacts.

The 0.2 μm device is shown in fig 4.



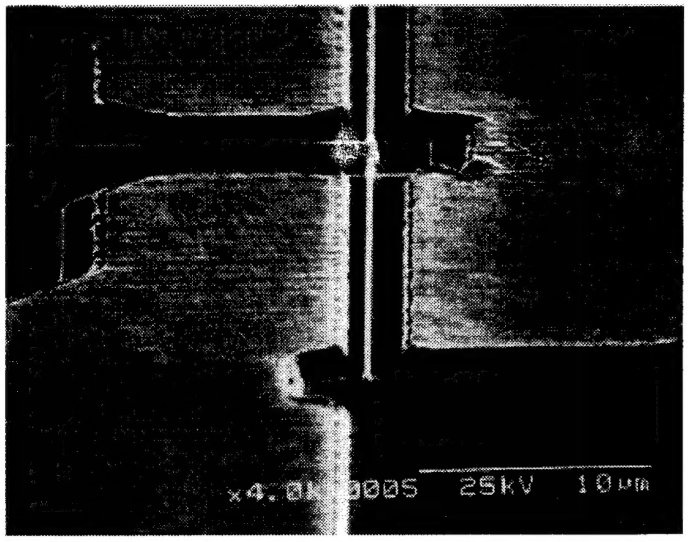


Figure 4. Device structure and the SEM micrograph of the device layout of the 0.2μm p^+-AlInAs/n-AlInAs/GaInAs JHEMT. In the layout view, the regrown regions are clearly seen as is the dry-etched, vertical sidewall of the mesa.

The full channel current is 450 mS/mm and the peak g_m at drain voltage of 1.5 V is 250 mS/mm. The maximum g_m is 300mS/mm at V_{ds} of 2V. The two terminal reverse breakdown is -19 V, the high value being attributable to regrown contacts. The 3 terminal on state breakdown is 5.2 V (for a source drain spacing of 2.7 μm). On-wafer RF measurements were done using a Wiltron 360 Network analyzer. A plot of gain versus frequency (V_{ds}=1.4V, V_{gs}=-2.4V) is given in fig 5 revealing the (f_τ) and (f_{max}) of 0.2μm gatelength device to be 62GHz and 105GHz, respectively.

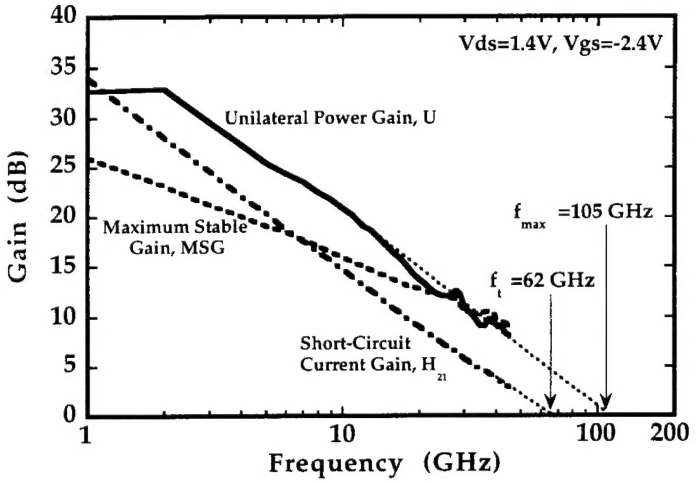


Figure 5. RF gain versus frequency for the 0.2μm gatelength JHEMT.

2. p+ AlInAs/n-AlInAs/GaInAs JHEMTs

Here the advantages of the p+-GaInAs gate electrode over a p+-AlInAs gate electrode are examined. The change to p+-GaInAs for the gate electrode has many advantages like lower gate resistance, reduced threshold voltage and a more flexible fabrication process.

The band diagrams of the p$^+$-GaInAs/n-AlInAs/GaInAs JHEMT and the p$^+$-AlInAs/n-AlInAs/GaInAs JHEMT are overlaid in Figure 6. First, by the removing the p$^+$-AlInAs, the valence band discontinuity at the p$^+$-GaInAs/p$^+$-AlInAs heterojunction is eliminated (This lowers the electron barrier slightly compared to p+-AlInAs gate but the electron barrier is still significantly higher than a conventional Schottky gate HEMT). This reduces the gate contact resistivity and, subsequently, the gate contact resistance, which is even more significant at short gatelengths.

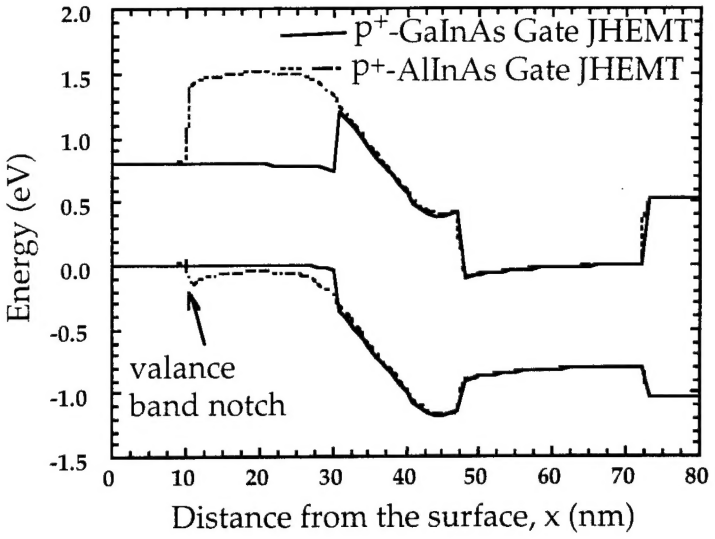


Figure 6. Energy band diagram comparing the p+-GaInAs/n-AlInAs/GaInAs JHEMT with the p+-AlInAs/n-AlInAs/GaInAs JHEMT.

Second, the thickness of the gate layer may be reduced by eliminating the p^+-AlInAs from the gate region. This, consequently, allows the gate recess etch to be achieved using wet etching. So, the triangular-shaped gate(which is used in the previous case where gate recess etch has to be done by RIE) may be replaced by a T-shaped gate, which has one-third the gate metal resistance. Therefore, the total gate resistance can be reduced by utilizing a single thin, p^+-GaInAs gate layer.

Third, the ohmic contacts to the channel may be alloyed through the thin p^+-GaInAs gate layer to obtain lower source and drain parasitic resistance. In the p^+-AlInAs/n-AlInAs/GaInAs JHEMT, the gate layers were too thick to achieve low contact transfer resistance to the channel. Thus, the ohmic contact regions were regrown unless additional etch-stop layers were added to the structure.

Finally, the p^+-GaInAs layer may be doped to much higher values than p^+-AlInAs. The p^+-GaInAs layers grown for the JHEMTs in this chapter were doped from $3x10^{19}$ to $1x10^{20}$ cm^{-3} using beryllium acceptor-impurities. The two consequences of higher acceptor doping are (i) less back depletion, and (ii) lower threshold voltage.

DC characteristics:

A plot of the three terminal I-V characteristics and g_m, I_{ds} versus V_{gs} (V_{ds}=1.5V) is shown in Figure 7 and 8 respectively. The full channel current and dc transconductance shown for a 100μm device is 460mA/mm and 520mS/mm, respectively. The improved transconductance, over p^+-GaInAs gate JHEMTs, results from reduced source resistance as well as the high aspect ratio.

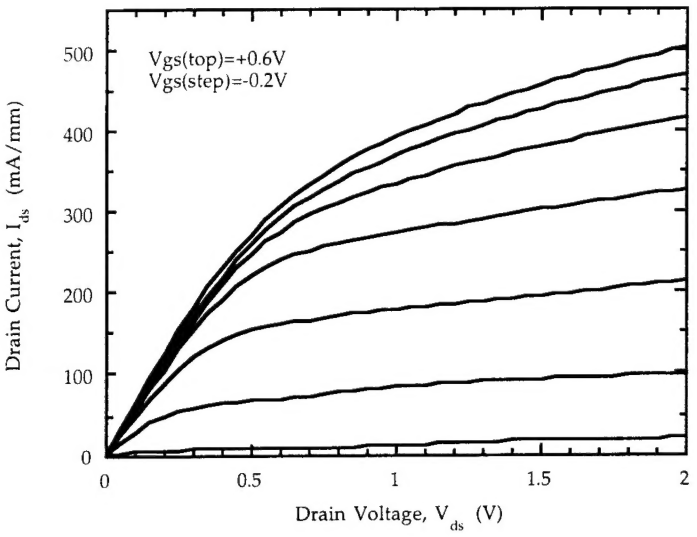


Figure 7. Three terminal I-V characteristics for the 0.2μm gatelength JHEMT.

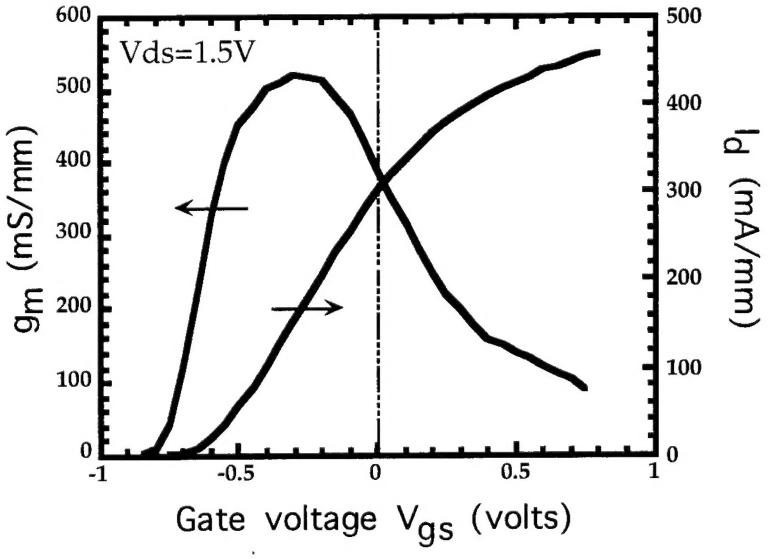


Figure 8. g_m, I_d vs V_{gs} for the 0.2μm gatelength JHEMT

The threshold voltage of the device is -0.8V. More importantly, the uniformity in threshold voltage is excellent with a standard deviation only of

13.7mV across the entire sample. This is as the threshold voltage of the JHEMT is established mainly by the MBE (layer thickness and doping) uniformity.

RF performance

The microwave s-parameters were measured on-wafer using a Wiltron 360 Network Analyzer. A plot of gain versus frequency (1-60 GHz) at V_{ds} = 0.8V, and V_{gs} =-0.3V, is shown in fig 8. From the short circuit current gain, the extrinsic f_τ of the 0.2μm single-doped p+-GaInAs/n-AlInAs/GaInAs JHEMT is 105 GHz. From the maximum stable gain (MSG) and the unilateral power gain (U), the unity power gain cut-off frequency (f_{max}) is 170 GHz. The peak f_{max} is over 200 GHz at V_{ds} = 1.0V (fig 9) and to our knowledge this is the highest f_{max} reported for a junction gate-barrier FET (JFET).

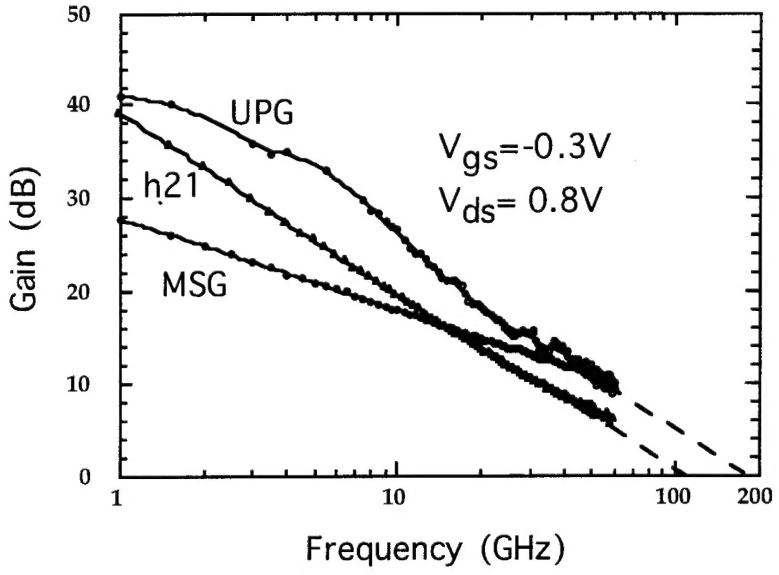


Figure 9. Gain versus frequency of the 0.2μm JHEMT

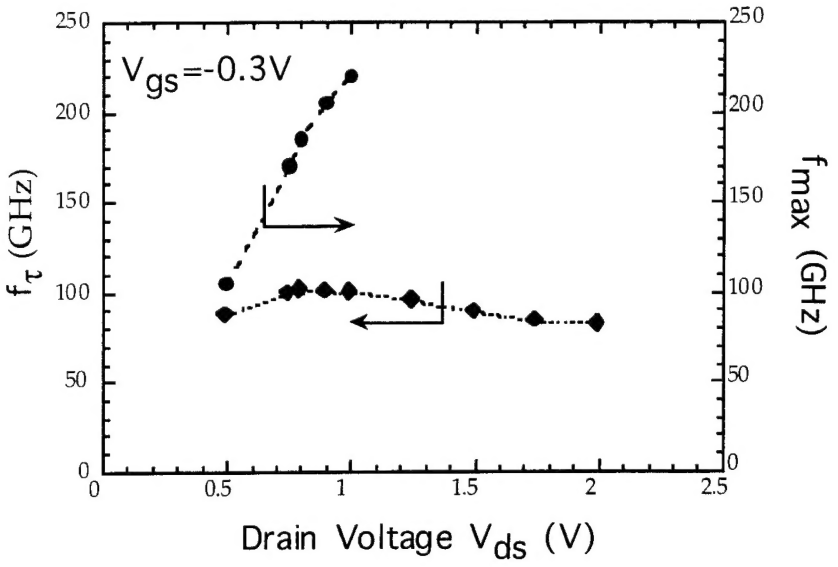


Figure 10. Bias dependence of unity gain cutoff frequencies.

Conclusion :

This investigation focused on the gate region of the InP-based HEMT. There are two distinct advantages of the JHEMT over the Schottky HEMT. First, the fixed gate-to-channel separation of the JHEMT determines important device parameters like V_{th}, C_{gs}, and G_{ds} which vary with the gate recess in the Schottky HEMT. Second, Junction HEMT allows the gate barrier of the HEMT to be tailored by selecting a gate material whose energy bandgap determines the gate barrier. The selection of a gate material also determines other relevant parameters (e.g. gate contact resistivity, acceptor doping capability) which affect important aspects of the device. The tradeoffs are the underlying focus in the following summary of the JHEMTs investigated in this work.

The two gate materials investigated were p^+-GaInAs (E_g=0.75eV) and p^+-AlInAs (E_g=1.48eV). If p^+-AlInAs is chosen as the gate layer, then a large gate barrier is achieved which is suitable for enhancement-mode operation. But, the high barrier comes at the expense of (i) high gate contact resistivity ($4x10^{-6}\ \Omega \cdot cm^2$), (ii) gate back depletion (120Å) which effectively reduces the aspect ratio, and (iii) a thick gate region (~600Å) since the AlInAs requires a graded transition to a p^+-GaInAs cap layer. However, if p^+-GaInAs is chosen as the gate layer, then the barrier is compromised to achieve (i) lower gate contact resistivity ($3x10^{-7}\ \Omega \cdot cm^2$), (ii) negligible gate back depletion (6Å), and (iii) a thin gate region (~200Å) since the p^+-GaInAs is also the cap layer.

List of Publications and Scientific Personnel

Publications:

1. Mishra, U.K. , Shealy, J.B , "InP-based HEMTs : Status and potential, Conference Proceedings", Sixth International conference on Indium Phosphide and Related Materials, 1994.

2. Shealy, J.B. et al, "Manufacturable, Low noise p+ InGaAs-AlInAs-n InGaAs Junction Modulated HEMT technology", Ultrafast Electronics and Optoelectronics, March 1995.

3. Shealy, J.B. et al, "Junction Heterostructures for High Performance Electronics", Solid State Electronics Proceedings of the Topical workshop on Heterostructure microelectronics.

4. Shealy, J.B et al, "0.2μm Gatelength, Non-Alloyed P^+-AlInAs/N-AlInAs/GaInAs JHEMTs with f_t=62GHz", Device Research Conference, June 1994.

Scientific Personnel:

1. Jeffrey Shealy, Degree earned while employed on the project : PhD, 1995, UCSB.